Environmental Health Perspectives
Vol. 8, pp. 123-131, 1974

Application and Evaluation of Portable Field Instruments for Measuring Forced Expiratory Volume of Children and Adults in Environmental Health Surveys

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In support of Health Effects Research Studies, pulmonary function tests are periodically administered to a large number of children. The ventilatory performance of these children is being evaluated by measuring the 0.75-sec forced expiratory volume ($FEV_{0.75}$) with a waterless mechanical volume spirometer used in conjunction with an electronic timing unit. During a 1-yr testing period, operation with the volume spirometer and the EPA designed electronic timing unit proved to be highly successful. The volume spirometer was found to be more advantageous in conducting tests at remote field stations than the water spirometer and other electronic instruments which measure flow rate with a transducer element. The volume spirometer is lightweight, easy to operate, and has the capability of easy and accurate field calibration when used in conjunction with the electronic timing unit. Presently the volume spirometer and EPA designed electronic timing package are employed in all Community Health and Surveillance System (CHESS) pulmonary function testing studies.

Introduction

Health Effects Research studies conducted in support of the Environmental Protection Agency's CHESS (Community Health and Environmental Surveillance Studies) program require large numbers of pulmonary function tests to be administered periodically at remote field locations. The tests are usually performed on elementary school students in their respective classrooms where interruptions and space requirements must be kept to a minimum *(1, 2)*.

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The purpose of this paper is to describe evaluation and selection of instrumentation best suited for performing the CHESS pulmonary function tests.

In the initial phases of the field testing, conventional water spirometers (Fig. 1) were used. Although the spirometers provided reliable data, considerable effort was required in transporting the heavy, bulky instruments to the various field testing sites. In addition, FEV (forced expiratory volume) values had to be manually determined from the inked tracing on the spirometer drums. A separate sheet of graph paper had to be attached to the spirometer drum for each new test.

Since large numbers of subjects were to be tested, the instrument had to be portable and to exhibit a high degree of accuracy. Consideration was given to pneumotachs, hot wire anemometers, and waterless spirometers. Major factors of consideration for acceptance of an instrument for use in the CHESS studies were: (1) that the instrument maintain prescribed accuracy over extended periods of time, (2) that operation of the instrument be simple, requiring a minimum level of field calibration, (3) that the instrument be portable and provide a direct digital readout in liters per unit time. This report will focus on the evaluations of instruments which were considered for updating the field testing instrumentation.

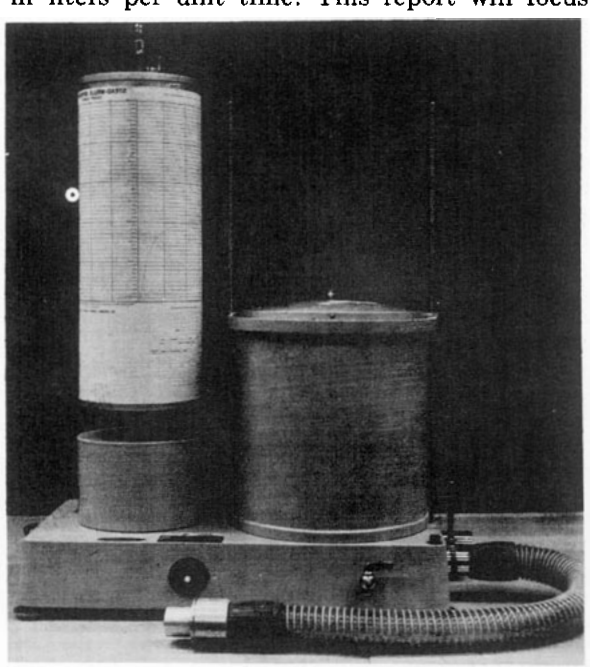

FIGURE 1. Collins Stead-Wells water spirometer used in early CHESS studies.

Modified Water Spirometer

Historically, water spirometers have been the most popular instrument for the measurement of lung volumes. These spirometers must be operated vertically with a counterbalance to offset the weight of the piston. The high inertial component of the weight results in lower frequency response and some inaccuracies during maximum breathing expansions. Also, the water spirometers evaluated had no electrical output available from which volume could be readily translated. FEV curves were plotted on a graph from which FEV was manually extrapolated (Collins water spirometer). Because of the water spirometer's advantages of simplicity and accuracy an attempt was made to modify the Collins 6-l. Vitalometer to provide an electrical output so that measurements could be made to three significant figures for $FEV_{0.75}$ and S/B $FEV_{1.0}$. A direct digital readout in liters requires that the volume instrument have an electrical output which varies linearly with a change of volume. The configuration normally is a potentiometer that changes resistance linearly as the piston moves. A 5000-ohm one-turn potentiometer was installed on the pulley of the Collins Vitalometer with a voltage source applied across the potentiometer. The center tap output of the pot was fed to a digital voltmeter. After repeated trials with a known air source, it was readily apparent that this configuration would not yield the accuracy and repeatability which was being sought. There was slippage on the pulley, poor accuracy at low volumes, and in addition, the mechanical pointer indicating volume in liters and the digital electronic readout never coincided. This divergence in readings precluded the possibility of using the mechanical indicator as a means for field calibration and adjusting the electronic package. It was concluded that the water spirometer provided more disadvantages than advantages, and that considerable time, effort, and money would have to be expended to make the water spirometer meet the basic criteria required for acceptance. At this

point, the water spirometer was abandoned and attention was focused on an electronic transducer sensing instrument.

Electronic Transducer Instruments

This class of volume-measuring instruments measures flow rate with a transducer sensing element. The transducer is the distinguishing feature for these instruments. They are sensitive devices which measure differential pressures or temperature changes. In order to make volume measurements, the transducer converts the flow signal from the sensing element to volume by means of electronic integration. The particular instrument chosen for evaluation was the NCG (National Cylinder and Gas Division of Chemtran Corp.) Pulmonary Function Indicator (Fig. 2). The instrument consisted of two parts: the transducer and the electronic package which houses the electronic circuitry, selection switches, and direct digital readout. The unit was highly compact and lightweight.

The transducer responds to temperature changes utilizing the principle of heat transfer. A platinum element which is part of an electrical circuit is heated greatly above ambient temperature. Heating is accomplished by passing current through the sensing element before expired air begins its flow across the transducer. When exposed to an air flow, the transducer element is cooled. This cooling changes the electrical resistance of the element which in turn varies the current. These changes of electrical characteristics relate to and measure the magnitude of the expired air flow.

The instrument's electronic and digital data readout are housed in a small carrying case. During actual testing the signals provided by the transducer are acted upon to produce the desired information which is stored in a memory system. At the instant the first molecules of the expired air come into contact with the transducer, a timing sequence is automatically initiated. The data is integrated to indicate total volume during the desired elapsed times. This information is stored and displayed on command.

These instruments are simple to operate. By changing a function switch, the $FEV_{0.75}$, $FEV_{1.0}$, and vital capacity can all be read directly from the digital readout meter since these values were stored in memory. The selector switch can be switched back and forth several times without disturbing the values in memory. Initial reaction to the instrument was highly favorable since it appeared to meet the basic criteria for acceptance. The instruments were shipped to New York City for field tests and comments. Field tests in New York City showed that certain precautions peculiar to the instrument must be taken if the instrument was to function properly. Among the major problems encountered during the New York field tests were erroneous readings caused by mucous formation on the hot wire and on the protective screen inside the transducer housing. This mucous buildup caused changes of air patterns in the transducer and also tended to insulate the hot wire from the air flow. Since transducer response depends upon the number of air molecules which strike the platinum wire, the forced expiratory values obtained were no longer valid. The protective screens could not be cleaned or replaced and thereby rendered the transducer useless. To eliminate this problem, an additional disposable screen was fitted to the opening of the transducer housing. The disposable screen could then be replaced when mucous accumulated. Also, a detergent aerosol for inhalation sold under the trade name Alevaire was found to dissolve the mucous on the transducer screens by immersion in the detegent for a period of 1−10 min, followed by a rinse in water. With the replaceable screens and the

FIGURE 2. Hot wire anemometer pulmonary function indicator.

use of the detergent, mucous formation was no longer considered a problem.

The most serious problem encountered was that of the pulmonary function indicator losing calibration. The trouble was traced to the transducer. The platinum sensing element mounted in the transducer is toroidal shaped and is held in place by three wires which make the electrical connections from the sensing element to the transducer housing. Once the instrument is calibrated, any change in geometry of the sensing element changes the calibration of the instrument. Mild bumps or jars could possibly cause such a change. To eliminate this problem, a covering of foam padding was installed around the transducer to absorb shock caused by rough handling.

The New York field tests of this instrument indicated a need for a simple way to calibrate and check the electronics and transducer while tests were being performed. Laboratory calibration prior to shipment was made by comparison to a water spirometer. Since it is impractical to have a heavy water spirometer on hand at each test site, an electronic quick check circuit was added to the pulmonary function indicator. A simulated signal of volume for a preset time period is sent to the digital readout and is compared with predetermined values. The electronic circuitry is then adjusted for the proper indication. No simple method existed of electronically field checking the accuracy of the transducer. Various methods were attempted but none proved completely effective.

In continued field tests, the problem of inaccurate measurements still plagued the instrument *(3)*. Further checks revealed that the instrument was temperature sensitive. Changes in ambient temperature caused changes in the readings. During the 1971 fall session of testing in New York, an electronic drift of ±10% was noticed in the instruments over the course of a testing day. The pulmonary function indicator could not maintain the manufacturer's specified 1% accuracy over the testing period. From all indications it appeared that instruments with the delicate transducers were not suitable for field use in the CHESS study. In order to collect valid data for CHESS during these field tests, the pulmonary function indicators were calibrated by a volume spirometer during all testing (before and after each class). Field testing also showed evidence that the accuracy of the instrument was dependent upon the flow patterns within the transducer housing. Any irregular turbulence in FEV air would give erroneous readings. An incorrectly positioned mouthpiece could cause such turbulence. Attention refocused on the volume spirometer.

Waterless Horizontal Spirometer

A search for a volumetric spirometer with an electrical output culminated with the purchase of a CPI (Cardio-Pulmonary Instruments Corp.) Model 200 precision dry-seal spirometer (Fig. 3). This spirometer is equipped with a large precision 3-in. infinite resolution film potentiometer which generates electrical output signals. The piston shaft is suspended on nylon wheels with sealed bearings. The Model 200 is equipped with a mechanical dial from which volume calibration and accuracy of electrical output can be continuously confirmed. Maximum capacity of the instrument is 12. l. with a linearity of 0.25% of full-scale readings. Comparison of readings by injecting a standard volume of air into the spirometer showed the instrument to be highly stable with no measurable drift.

The CPI Model 200 spirometer is a simple device. The physical makeup consists of a piston, with a driving rod, a set of pulleys, dial cord for attachment to the pulleys, a return spring, a precision potentiometer, and mechanical

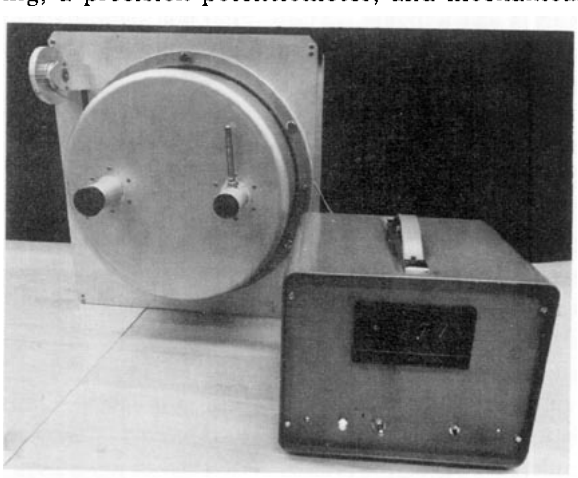

FIGURE 3. Present spirometer (CPI) and EPA-designed timer used in CHESS pulmonary measurements.

readout dial. There are two input ports: one is for attachment of the hose through which expired air passes from the subject to the instrument through a one-way valve; the second port is plugged by a rubber stopper and removed to allow the expired air to escape after the measurement is taken. The second intake port was designed into the instrument to provide the addition of a CO_2 absorber for rebreathing studies. When expired air is passed into the instrument the piston is driven to the rear and displaced in volume equal to the volume of air injected into the instrument. As the piston moves to the rear, the driving rod causes the pulleys to move, which, in turn, causes the potentiometer and mechanical dial to turn. Once activated the instrument will stay in this position until the expired air is allowed to escape from the drum. This is accomplished by removing the rubber plug from the second port. The return spring of the piston automatically returns the instrument to zero state. In simplicity and accuracy, the CPI instrument has many advantages over the water spirometer. The weight and inconvenience of water are eliminated and direct readings can be taken from the CPI spirometer, while readings have to be extracted from the graph on the water spirometer. Although readings on the CPI can be accurate only to two significant figures (since the dial is marked in tenths of liters) there is no injected error in the data due to the interpolation of time and value. The Model 200 CPI spirometer can be operated more accurately as a volume measuring instrument than the water spirometers which were initially used in CHESS pulmonary function testing.

The Model 200 CPI spirometer can also be purchased as a component of Model 200 systems spirometer which is designed to meet the requirements for multiphasic screening and measuring. The S/B systems spirometer includes a self-contained electronics S/B module which provides electrical outputs for flow, volume and totalized volume (MVV). Correction of electrical outputs to body temperature and pressure saturated with water vapor is accomplished by setting a front panel control switch to the spirometer temperature. Consideration was given to the purchase of the spirometer systems for use in the CHESS studies; however, cost was prohibitive. It was determined that an electronic package to provide digital readout to three significant figures for $FEV_{0.75}$, $FEV_{1.0}$, and total capacity could be developed and constructed by in-house staff for a relatively low cost. Design of the electronic package began in November 1971 and the prototype models were built and placed in field use in February 1972.

The major components of the EPA-designed electronic package are (1) digital voltmeter that measures from 0 to 1.999 V; (2) timing board to provide signals at 750 and 1000 msec; (3) a power supply to provide necessary dc voltages. The package connects to the CPI spirometer by a phone jack. The only other connection that must be made is to connect the electronics package into a commercial power source of 115 V ac. The electrical operation is relatively simple. Since the spirometer contains an infinite resolution potentiometer and rotates from 0 to 360° for 0–12 l., a dc voltage of 1.2 V is applied across the potentiometer. This arrangement equates a dc voltage to volume in liters. Zero volts equals zero volume, and 1.2 V dc at the center tap of the potentiometer equals a volume of 12 l. The relationship is linear. The voltage appearing at the center tap of the potentiometer varies as the piston of the spirometer is displaced and this voltage is applied to the digital voltmeter. The requirement at this point is to stop the digital voltmeter from counting at 0.75 sec. This timing voltage is generated by the timing board. The input to the timing board is taken also from the center tap of the potentiometer on the spirometer. The instant the digital voltmeter starts to read, the output of an operational amplifier with very high gain changes from +15 V dc to −15 V dc. This reversal turns off an electronic switch (transistor) which allows a capacitor to charge through a series resistor. Once the capacitor charges to approximately 5 V dc, it triggers a unijunction oscillator which continuously sends pulses to a flip-flop stage. On the first pulse from the oscillator, the flip-flop stage is triggered producing a 3.5-V dc positive voltage which is applied to the hold circuit of the digital voltmeter. This stops the voltmeter from counting and holds the read-out on the meter. Timing for 750 and 1000 msec is accomplished by adjusting a series potentiometer in the resistor-capacitor network. Timing is measured

and adjusted from the time the operational amplifier changes states to the point when the digital voltmeter stops counting. The reading on the voltmeter will remain even though the spirometer is cleared of expired air and returns to the zero state. To return the voltmeter to the zero state, a reset button is provided on the front of the package. Depressing this spring loaded switch resets the flip-flop circuit, removing the hold voltage from the meter which returns the meter to zero position. Internally, the package contains a slide switch which selects the time of 750 or 1000 msec. Schematics and wiring diagrams are shown in Figures 4–6. The parts lists is given in the Appendix).

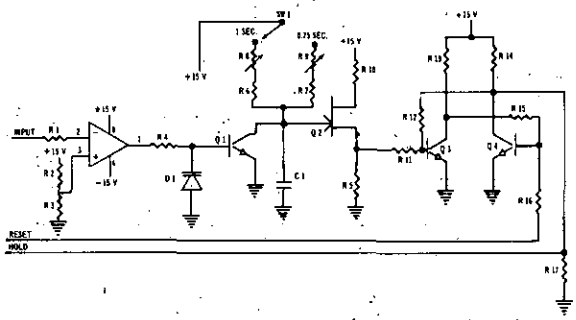

FIGURE 4. Schematic diagram for the timing board.

After repeated tests which were administered in the laboratory on the timing circuits, the data recorded indicated changes in time in the microsecond range. Subjected to extreme temperature changes, 32°F to 150°F, changes in time never exceeded more than 1% of the readings recorded at normal room temperature. After calibration of the electronic package to the spirometer was accomplished, injections

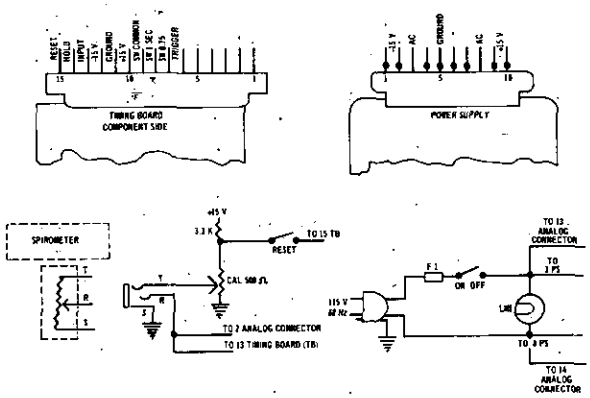

FIGURE 5. Wiring diagram: chassis.

of a standard volume of air into the spirometer showed that the mechanical readout on the spirometer and the electrical readout of the voltmeter were identical.

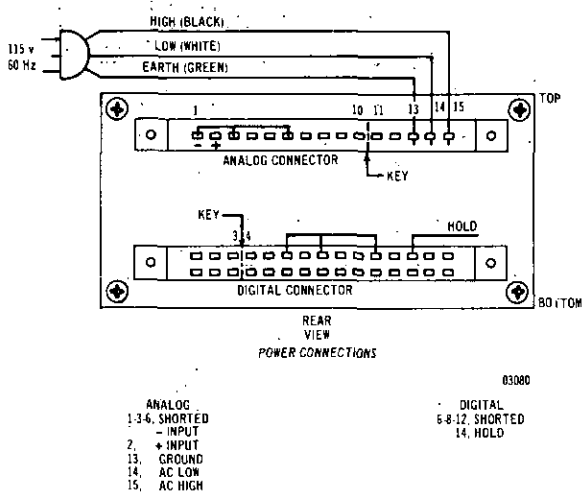

FIGURE 6. Wiring diagram: digital voltmeter.

Repeated tests indicated that the air spirometer using the EPA-designed electronics package could function as an adequate and suitable measuring system for use in the CHESS studies. The electronic linearity can be checked and calibrated in the field by using the mechanical volume indicator on the spirometer drum. Accuracy of the timing circuit is measured with a frequency meter.

In February 1972, four instruments were shipped to New York and two instruments to Chattanooga for use during the early spring testing session. An unanticipated problem that immediately arose was the accumulation of moisture in the hose which could be inhaled by subjects. Moisture collection and the inhalation of this moisture was viewed as being socially unacceptable. This meant that the hose would have to be washed and dried after each class was tested. The solution to this problem was the insertion of a one-way valve at the upper end of the hose. Although moisture accumulates in the valve, it is much simpler to wash the valve with alcohol after each class than to wash the hose. The valves were placed in use in both New York and Chattanooga for the early spring tests.

A report from Chattanooga on March 9, 1972, showed no problems with the equipment.

Valves were washed after each class, and hoses were washed and dried at the end of each day of testing. In Chattanooga operators disassembled the front drum on the spirometer after every 3 days of testing and noted the accumulation of moisture. Total moisture accumulated in 3-day periods amounted to only 2 or 3 ml. Calibration of the instrument and electronic package was checked each morning before testing began, before each class testing, and during testing when the validity of the readings was questioned. The instruments required no adjustments.

Because of these positive results, a decision was made to employ the CPI volume spirometer in all CHESS pulmonary function testing studies. Ease of calibration made the instruments ideal for remote field testing.

The results of the spring testing period shows an overall successful operation. Except for minor difficulties, pulmonary function schedules were never in jeopardy. The instruments performed well. When the instruments were returned to CHESS headquarters, they were completely rechecked. Timing circuits have all remained well within the 1% tolerance of the 750 millisecond time period. Spirometers have remained mechanically intact during handling and shipping.

One final concern with the system was the error that could be introduced by back pressure of the CPI spirometer and the one-way valve. Further tests were conducted inhouse to measure back pressure of the system by use of a Statham transducer. Adult subjects performed forced vital capacity maneuvers with the CPI spirometer and Statham transducer in series. Peak flow was about 9–11 l. sec recorded with a Medical Science spirometer. The results of several measurements are shown for comparison in Table 1.

The average peak flow rate of elementary school children is less than the 9–11 l./sec of the adult subjects used in the back-pressure tests. (Peak flow for children is less than 5–6 l./sec.) Since back pressure increases with peak flow rate, the back pressure of the systime would be considerably less for measurements made on the school children. With results of back pressures as shown in Table 1, the CPI system along with the one-way valve, should induce no significant error due to resistance to flow.

Table 1.

System	Maximum back pressure, cm H_2O	Number of trials
CPI spirometer with 81 cm corrugated tubing (1.5 in. id and valve)	5.4	8
CPI spirometer with 81 cm corrugated tubing	1.9	5
81 cm corrugated tube (1.5 in. id)	0.9	3
Mesh type pneumotachograph	1.6	4
Fleisch type 3 pneumotachograph with 76 cm corrugated tube (1.5 in. id)	2.5	3
Med Science wedge-type spirometer with 10 cm of 1.25 in. and 51 cm of 1.5 in. id tubing.	0.55	3

Temperature Effect

During development and evaluation, consideration was given to cooling and contraction of the expired air volumes as it leaves the mouth and enters a measuring system. For the hot wire anemometer, cooling has little effect on the measured FEV values. The hot wire is heated much above body temperature and the transducer is located very close to the mouth.

With the spirometers which use a tube (approximately 91 cm in length) to get the air from the mouth to the measuring cylinder, cooling and resulting volume contraction is significant. Laboratory measurements have shown that the expired air reaches room temperature very near the entrance of the 91 cm tube. A thermometer was installed on each of the spirometers and volumes are corrected back to body temperatures (BTPS). During field tests, spirometer temperature is recorded during each class testing.

Conclusion

Laboratory and field pulmonary function testing have shown the waterless mechanical volume sensing spirometer coupled with automatic electronic readout to be superior for large numbers of field pulmonary function tests where instrumentation must be moved constantly during testing. The system can be calibrated in the laboratory with a primary standard before testing sessions begin, and can be checked at any time during testing by utilizing the mechanical indicator located on the spirometer. The system is light-weight, portable, durable, and simple to operate.

Appendix: Parts List

Component	Specifications	Source
Power supply	Model DCP-15M w/cord-Pac connector	Power Mate Corp.
Digital voltmeter	Model 200A-3 w/options, A3, D2	Newport Lab Inc.
Timing board		
R1, R4, R12, R13, R14, R15, R16	10K, 1/4W, 5%	
R2	47K, 1/4W, 5%	
R3	10 ohm, 1/4W, 5%	
R6	Selected for 1 sec	
R7	Selected for 0.75 sec	
R8, R9	100K Trimpot, Bourns 276-1-104	
R10	1K, 1/4W, 5%	
R11	4.7K, 1/4W, 5%	
R17	3.9K, 1/4W, 5%	
C1	1 μf, 50 V dc	
D1	Diode, GE DT230B	
Op-Amp	N5558V, Signetics	
Q1	2N2925	
Q2	2N4870	
Q3, Q4	MPS 6515	
SW1	Slide Switch, Stackpole, 55-26-1	
Edge Connector-Cinch 50-15A-20		
Chassis		
1 Switch on/off	Arrow Hart, 20994.LH	
1 Dial Light	IDI 2150-A3	
1 Fuse Holder	Littlefield 341001A	
1 Chassis	Bud AC406	
1 Cabinet	Bud WA-1542	
1 AC Cord	Belden 172375	
1 Switch (Reset)	Grayhill 30-1	
1 Phone Jack	Switchcraft S-12B	
1 Potentiometer	Cal Pot, Allen Bradley Jan 1N200P-501NA	

Acknowledgment

The authors gratefully acknowledge the cooperation and assistance of Dr. John Brooks, Bio-Medical Research Branch, Environmental Protection Agency, for providing support in equipment evaluation.

Mention of a specific commercial product or a company name does not constitute endorsement by the Environmental Protection Agency.

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